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Biochar impacts on carbon dioxide, methane emission, and cadmium accumulation in rice from Cd-contaminated soils; A meta-analysis

Muhammad Athar Khaliq[a], Ibtisam Mohammed Alsudays[b], Haifa Abdulaziz Sakit Alhaithloul[c], Muhammad Rizwan[d], Jean Wan Hong Yong[e,*], Shafeeq Ur Rahman[f], Muhammad Sagir[g], Safdar Bashir[h], Habib Ali[i], Zuo Hongchao[a,*]

[a] College of Atmospheric Sciences, Lanzhou University, Tian-shui South Road, Lanzhou 730000, PR China
[b] Department of Biology, College of Science, Qassim University, Burydah 52571, Saudi Arabia
[c] Biology Department, College of Science, Jouf University, Sakaka, Aljouf 2014, Saudi Arabia
[d] Department of Environmental Sciences, Government College University Faisalabad, Faisalabad 38000, Pakistan
[e] Department of Biosystems and Technology, Swedish University of Agricultural Sciences, Alnarp 23456, Sweden
[f] Water Science and Environmental Engineering Research Center, College of Chemical and Environmental Engineering, Shenzhen University, Shenzhen, China
[g] Department of Mechanical Engineering, Khwaja Fareed University of Engineering & Information Technology, Rahim Yar Khan, Pakistan
[h] Department of Soil and Environmental Sciences, Faculty of Agriculture, Ghazi University, Dera Ghazi Khan 32000, Pakistan
[i] Department of Agricultural Engineering, Khwaja Fareed University of Engineering & Information Technology, Rahim Yar Khan, Pakistan

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ABSTRACT

Climate change and cadmium (Cd) contamination pose severe threats to rice production and food security. Biochar (BC) has emerged as a promising soil amendment for mitigating these challenges. To investigate the BC effects on paddy soil upon GHG emissions, Cd bioavailability, and its accumulation, a meta-analysis of published data from 2000 to 2023 was performed. Data Manager 5.3 and GetData plot Digitizer software were used to obtain and process the data for selected parameters. Our results showed a significant increase of 18% in soil pH with sewage sludge BC application, while 9% increase in soil organic carbon (SOC) using bamboo chips BC. There was a significant reduction in soil bulk density (8%), but no significant effects were observed for soil porosity, except for wheat straw BC which reduced the soil porosity by 6%. Sewage sludge and bamboo chips BC significantly reduced carbon dioxide (CO_2) by 7–8% while municipal biowaste reduced methane (CH_4) emissions by 2%. In the case of heavy metals, sunflower seedshells-derived materials and rice husk BC significantly reduced the bioavailable Cd in paddy soils by 24% and 12%, respectively. Cd uptake by rice roots was lowered considerably by the addition of kitchen waste (22%), peanut hulls (21%), and corn cob (15%) based BC. Similarly, cotton sticks, kitchen waste, peanut hulls, and rice husk BC restricted Cd translocation from rice roots to shoots by 22%, 27%, 20%, and 19%, respectively, while sawdust and rice husk-based BC were effective for reducing Cd accumulation in rice grains by 25% and 13%. Regarding rice yield, cotton sticks-based BC significantly increased the yield by 37% in Cd-contaminated paddy soil. The meta-analysis demonstrated that BC is an effective and multi-pronged strategy for sustainable and resilient rice cultivation by lowering greenhouse gas emissions and Cd accumulation while improving yields under the increasing threat of climate change.

1. Introduction

Rice is an important cereal crop and is a major contributor to food security (Jalil et al., 2023;Hussain et al., 2023). Climate change impacts food security globally by changing food supply, consumer accessibility, and food quality, eventually leading to unsustainable agriculture. The rice production system is the most susceptible agroecosystem (Saud et al., 2022), and climate change significantly affects rice productivity (Hussain et al., 2023). According to the Inter-government Panel on Climate Change's Fifth Assessment Report (Fu et al., 2015), the global temperature increased by around 0.85 °C from 1880 to 2012. This warming environment harms world food production (Pachauri and Meyer, 2014), particularly rice yield (Hussain et al., 2021). From 1951–2017, China had an annual surface temperature rise of 1.6 °C due

* Corresponding authors.
E-mail addresses: jean.yong@slu.se (J.W.H. Yong), zuohch@lzu.edu.cn (Z. Hongchao).

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to global climate change (Tao and Zhang, 2013; Zhao et al., 2017). Each degree Celsius rise in climatic temperature throughout the growing season decreased rice grain yield by 10% (Peng et al., 2004). Rice is a staple food for almost fifty percent of the world's population and it is grown in over a hundred countries (Hussain et al., 2022), with Asia accounting for 90% of global rice production (Fukagawa and Ziska, 2019). China is the world's largest rice producer, consumer, and importer. Approximately 80% of the Chinese population consumes rice as a regular staple food and greater rice yield is the cornerstone of global and Chinese food security (Chen et al., 2017).

Climate change significantly impacts global rice production which is influenced by both human-induced and natural factors. Agriculture is an anthropogenic activity that emits greenhouse gases (GHGs), and rice fields constitute a significant GHG sink. Carbon dioxide (CO_2) is the most important anthropogenic greenhouse gas that affects climate change and global warming. CO_2 is mainly emitted from the combustion of fossil fuels but land use changes also have an important share in atmospheric CO_2 (Peters et al., 2015) Methane (CH_4) is the second most important greenhouse gas after CO_2 and contributes about twenty percent to global warming (Houghton et al., 2001). Globally, about 31–112 Tg per year of CH_4 emission from paddy soils was estimated to account for 30% of total emissions (Gupta et al., 2021; US, 2006). Applying synthetic fertilizer, residue burning and tillage practices contribute to CO_2 and CH_4 emissions from paddy soil (Xie et al., 2013; Gupta et al., 2021). Heavy metal and metalloid contamination is detrimental to soil, vegetation, and human health (Mishra et al., 2019; Rahman, Nawaz, et al., 2022). The occurrence of hazardous heavy metals and metalloids from anthropogenic (e.g. soil nutrient levels, water pollution) and natural events affects agricultural lands through the accumulation of various plant components over time (Yong et al., 2010; Liu et al., 2012; Song et al., 2019; Rahman et al., 2024). Due to its toxicity, Cd is also a major issue in soil-rice cropping systems (Simon et al., 2016). Cd is one of the most likely heavy metals to move from paddy soil to rice grains. The translocation of Cd into rice plants hinders the physical and physiological parameters of plants, such as hindering leaf photosynthesis, plant height, and root length, leaf size, plant biomass, ultimately reducing grain yield (Liu et al., 2015; Rahman et al., 2023; Shaghaleh et al., 2024). Climate change mitigation and food security not only require the lowering of CO_2 and CH_4 emissions from the atmosphere, but concomitant reduction in heavy metals and metalloids is also necessary for providing safe food to humans and other organisms.

For sustainable and resilient cultivation, biochar (BC) is an effective tool for soil amendment to improve soil properties and plant performance especially during unfavourable environmental conditions (Abbott et al., 2018 ; Sani et al., 2023;Hasnain et al., 2023). Biochar is a carbon-enriched matter produced by the controlled pyrolysis of organic biomass such as crop residues, manure, and wood (Ghodake et al., 2021). The worldwide biochar market was worth USD 406.5 million in 2020, and it is predicted to grow to USD 885 million by 2027, with a compound annual growth rate of 11.8% between 2021 and 2027 (Phadtare and Kalbande, 2022). As a soil additive, BC usage is increasing over the years to maintain soil health, sequestering organic and inorganic contaminants, and to reduce greenhouse gas (GHG) emissions (Xie et al., 2013; Fang et al., 2016; Abbott et al., 2018). BC plays an important role in increasing the soil organic carbon (SOC), also called SOC sequestration, the process in which various techniques or amendments are applied in the toxic metal-contaminated soils to incorporate the organic carbon into soils that ultimately transform as a long-living C-pool, otherwise, it would be released as CO_2, that is considered as the main source of global warming (Gross et al., 2021; Ji et al., 2023; Zheng et al., 2022). BC incorporation in soils influences soil structure, texture, porosity, and density (Alghamdi et al., 2020). Due to the large surface area and high porosity, the addition of BC in rhizosphere provides conducive habitats for beneficial microorganisms (plant growth promoting bacteria, mycorrhizal fungi) and binding sites for macro-nutrients such as N and P (Atkinson et al., 2010; Xu et al., 2018; Sani et al., 2023). Moreover, the alkalization of soil, increase in electrical conductivity, and cation exchange capacity are significant aspects of BC when amended in agricultural soil (Domingues et al., 2020).

Biochar incorporation into the paddy soils may enhance rice production by improving the water holding capacity and micronutrient availability to the plants and reducing the soil bioavailable Cd, its uptake, and accumulation in rice organs (Rassaei, 2022a, 2023d). BC application increases the phyto-stability of heavy metals and reduces their transfer and accumulation in edible parts of plants (Rassaei, 2023c). The bioavailability of heavy metals and metalloids in soil is dependent upon the soil properties: adsorption, precipitation, surface sorption, and organic matter contents (Rahman et al., 2022; Rassaei, 2022a). The sorption behavior of heavy metals and metalloids is also affected by several soil properties such as pH, clay, and organic matter content (Rassaei, 2022b; Shaghaleh et al., 2024). Previous research demonstrated that BC is a good heavy metal adsorbing material, especially in standing water conditions (Rassaei, 2023a; Sohi et al., 2009). BC has strong ion exchange capacity, large specific area, and high porosity due to which it can reduce GHG emissions (Rassaei, 2023b). GHG emission from the soil was dependent on the soil microbial activities such as nitrification, denitrification, aerobic and anaerobic respiration, and oxidation of methanogens (Rassaei, 2023c). Interestingly, BC addition into the soil could release dissolved organic carbon into the solution, which is important for regulating microbial activities. BC application also provides favourable rhizospheric conditions to soil microbes for their various metabolisms (e.g. improving nutrient bioavailability) and leading to improved survivorship in polluted soils (Xu et al., 2018; Luo et al., 2021). Thus, BC application could change the physiochemical and biological properties of the agricultural soils, GHG emissions, and heavy metals bioavailability and accumulation in the paddy soil-rice system (Xie et al., 2013). However, the pyrolysis conditions and feedstock type of BC would have differential effects on CO_2, CH_4 emissions, Cd bioavailability, and accumulation in rice plant parts.

Therefore, this meta-analysis aimed to collate salient baseline information and clarify the effectiveness of BC on GHG emission, Cd accumulation, and rice production with the help of current literature. Previously, many scientists have investigated the effects of some specific BC addition on Cd-contaminated and GHG emissions in the paddy soils (Duan et al., 2023; Yuan et al., 2021), but did not consider holistically the effects of various BC on Cd-contaminated soil's GHG emissions, Cd bioavailability and accumulation in rice. For that reason, a systematic analysis is needed to investigate the impacts of adding BCs on (i) CH_4 and CO_2 emission, (ii) Cd availability and accumulation in rice, and (iii) rice yield in Cd-contaminated paddy soils. To substantiate our views and objectives, we performed a meta-analysis based on 1576 paired individual experimental observations extracted from 100 previously published articles regarding Cd-contaminated and GHG emissions from paddy soils.

2. Materials and methods

2.1. Data sources and compilation

The current meta-analysis assessed the biochar effects on CH_4 and CO_2 emission and Cd availability and accumulation in rice. For this purpose, literature published during 2000–2023 was searched and collected from Web of Science, Google Scholar, and ScienceDirect using keywords such as biochar AND methane emission AND carbon dioxide emission AND cadmium contaminated soil AND cadmium accumulation in rice plant parts. Moreover, all the articles' references were searched to uncover the most relevant publications. Selected articles data (means + SD values + sample size) for biochar effects on CH_4 and CO_2 emission and Cd availability and accumulation in rice compared with the control treatments group. If the standard error was provided rather than SD in the article, it was converted by using the equation $SD = SE \times \sqrt{n}$ (n, the number of replicates). For the variance (V) calculation, the following equation was used:

$$V = (N_c + N_t)/(N_c \times N_t) \quad (1)$$

Where N is the number of replicates for the control group (N_c), and the treatment group (N_t) (Wang et al., 2016).

In this meta-analysis, although 350 published articles were collected, data from only 100 articles were used for further analysis. About 250 articles were not included due to various scientific reasons: some issues wuth research methodology, inadequte findings, and unclear conclusions. Data was carefully extracted from the text, tables, and graphs including different parameters such as biomass feedstock, pyrolysis temperature, application rate, application methods, soil texture, soil organic carbon (SOC), soil pH categories, and biochar pH categories, CH_4 and CO_2 emission, and Cd availability and accumulation in rice with biochar and control treatments in Cd contaminated soils. GetData Plot Digitizer software was later used to extract the selected data from the figures. The extracted data was evaluated, reviewed, and analyzed for the required parameters; we finalized a set of 1576 observations from the 100 articles. After the compilation of data, the inclusion-exclusion principle was applied by using the following criteria: I). At least three replications' data for all the selected parameters were included; II). Random effect was used; III). All the data sources are available in the published article (Supplementary Table 1).

2.2. Data grouping

This study used published data to explore the effect of BC on CO_2 and CH_4 emission from Cd-contaminated paddy soil and the accumulation of Cd in rice plant parts. The following variables were compared among the selected studies, including biomass feedstock, pyrolysis temperature, application rate, application methods, soil texture, soil organic carbon (SOC), soil pH categories, and biochar pH categories. These variables were categorized into several sub-groups for data homogenization, their means, standard deviations (SDs), or standard errors (SEs) were used for further analysis.

2.3. Combined effect size analysis

For the computation of standardized mean difference regarding combined effect size between the treatments and control groups was calculated. As a measure of effect size (Hedges et al., 1999), the natural log-transformed response ratio (RR), and percentage change were computed from selected studies as follows:

$$RR = \ln(X_t/X_c) \quad (2)$$

$$\%Change = ([RR - 1] \times 100\%) \quad (3)$$

Where X_t represents the mean values of BC-treated Cd-contaminated soils, X_c is the mean of control treatments (Borenstein et al., 2009). The mean values and standard deviation data for biomass feedstock, pyrolysis temperature, application rate, application methods, soil texture, soil organic carbon (SOC), soil pH categories, biochar pH categories, Cd bioavailability, Cd accumulation in rice plants, and CO_2, CH_4 emission in paddy soil rice system were used to find out the overall response effect of biochar relative to the control treatment. Additionally, RR = 0 represents a null effect size, RR < 0 showed a negative effect size, and if RR > 0, the effect size was positive, respectively, following the addition of BC, were shown in the new data analysis (Supplementary Fig. 1 - 10). The higher negative values demonstrated lower BC effects over the study parameters.

2.4. Publication biasness removal

For the removal of biased effect size, metadata was processed through funnel plots and Begg's tests to eliminate the publication biasness (Tozser et al., 2017; Yu et al., 2018). The trim and fill method was used in the funnel plot, which removes the significant asymmetry and provides a symmetrical effect size with their standard errors (Duval and Tweedie, 2000a). The trim and fill method was applied through a series of simple calculation steps. In the first step, the weighted mean effect size was calculated and used as an estimation of the effect size of a variable. The estimated effect size was subtracted from each effect size in the meta-analysis. The negative values of the obtained data were calculated and arranged systematically from smallest to the largest. All positive values were then rearranged and summed up before the negative values were separated and data processing was completed as explained by Duval (2005). The data abnormalities or outliers were removed through the shearing technique and the missing data values besides the central part of the funnel plots were filled as described by Duval and Tweedie, (2000b).

2.5. Meta-analysis

Data Manager 5.3 software was used to analyze the data (Rosenberg, 2005). Forest plots were prepared from the selected studies data for the CO_2 and CH_4 emission from Cd-contaminated paddy soil and the accumulation of Cd in rice plant parts, including biomass feedstock, pyrolysis temperature, application rate, application methods, soil texture, soil organic carbon (SOC), soil pH, and the biochar pH categories from the selected studies (Rosenberg, 2005). Our study showed the overall changes (%) considered at 95% confidence intervals (didn't overlap the mean zero line) for all the parameters, and groups and sub-groups significance level was considered at non-overlapping of confidence intervals (Kumar et al., 2018; Rahman et al., 2023; Yuan et al., 2021). Vertical lines represent no effect at zero (BC treatments effect over CH_4, CO_2, and Cd in soil and accumulation in rice was equal to the control group) for the studies data included in this meta-analysis. The variance between the studies was statistically significant so the random effect model was used to calculate the effect sizes and assessed the BC effects over the CH_4, CO_2, rice plant yield, available Cd in soil, and its accumulation in rice plants. The heterogeneity of the true effect size between the studies was quantified by using a p-value linked with heterogeneity test (Q) and variance values. We considered a common effect size for the groups of studies for BC and CH_4, CO_2, soil bioavailable Cd, and Cd accumulation in rice with p-value ≤ 0.05, indicating the heterogeneity of effect sizes among various studies or groups of studies. The V-values indicated the homogeneity test that depends neither on the effect size nor the number of studies, and the V-values approximately up to zero represent the homogeneity between the effect sizes (Eq. 1).

3. Results

3.1. Overall changes (%) in response to biochar application in the paddy rice field

In general, biochar significantly increased the rice yield by over 20%; while in the case of CH_4 emission by 2% and soil respiration (CO_2) were significantly reduced by 7–8% (Fig. 1). A significant change of soil SOC and bulk density was observed against all subgroups (BC feed-stock, pyrolysis temperature, application rate, application method, BC carbon contents, soil texture, soil pH). Moreover, a significant change in Cd-contaminated soil pH was found in the case of biochar addition. Our meta-analysis predicted that a significant reduction of Cd in rice tissues i.e., roots, shoots, and grains was observed.

3.2. BC application improves the physio-chemical properties of paddy soil

The soil physical and chemical properties play a significant role in rice production, and BC addition to paddy soil improves the soil's physio-chemical properties and enhances crop productivity (Chang et al., 2021). The soil pH, SOC, bulk density, and soil porosity are the

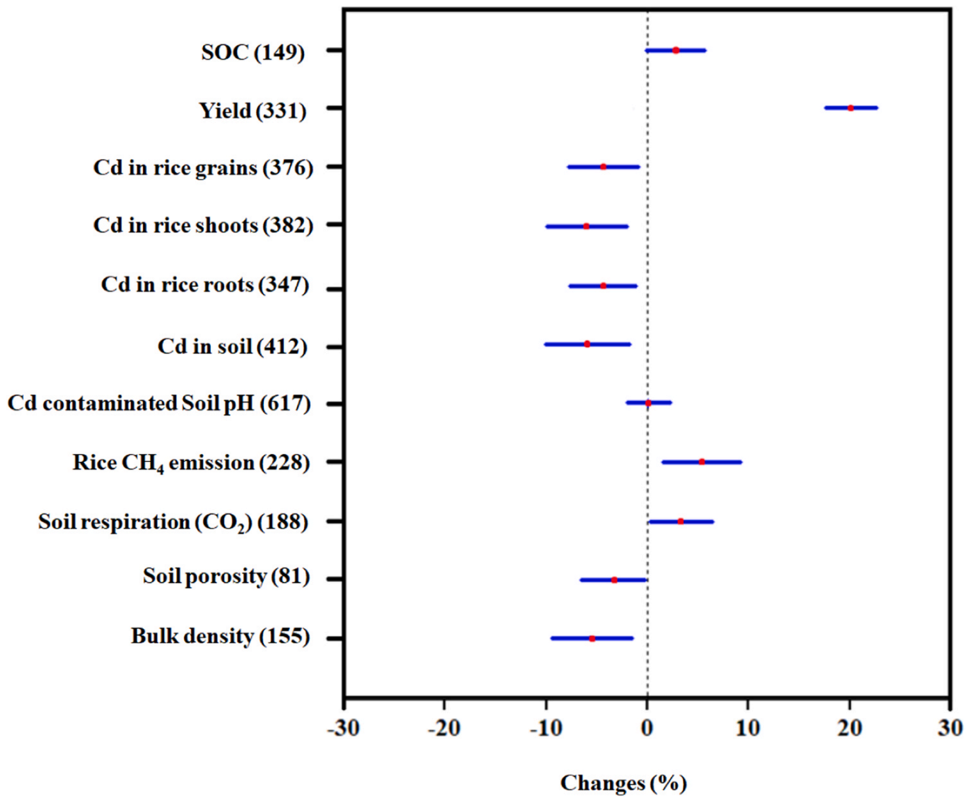

Fig. 1. Overall effects of biochar on yields, Cd in grains, roots, shoots, and soil, rice methane (CH_4) changes, soil organic carbon (SOC), soil-pH, soil porosity and density, and soil respiration (CO_2). The number in brackets indicates the number of paired observations. Error bars indicate 95% confidence intervals. Variables were significant at $p < 0.05$, if error bars did not overlap with zero.

most important physio-chemical properties that maintain soil aggregate stability and health (Abbott et al., 2018; Guo et al., 2019). Therefore, our meta-analysis was focused on examining the soil properties. Specifically, BC held free bases like calcium, potassium, and magnesium and, after being applied to paddy soil; eventually increasing the pH due to exchangeable bases (Shetty and Prakash, 2020). In general, pH is one of the most important soil properties influenced by the BC amendments. Among different feedstocks used in paddy soil, the sewage sludge pyrolyzed at more than 600 °C, significantly increased pH by 18% (Fig. 2). The remaining feedstocks minimally increased the soil pH except for eggshell and sunflower seedshells-derived materials BC. Regarding pyrolysis temperature, the maximum increase in pH (10%) of paddy soil was observed when feedstock was pyrolyzed at high temperatures (>600 °C). In contrast, the lowest increase was observed in the case of feedstock pyrolyzed in the temperature range of 350–600 °C (3%) (Fig. 2). The varying rate of BC application also influenced soil pH, and BC applied as 51–100 t/ha and 101–151 t/ha significantly enhanced soil pH by 10% and 5%, respectively (Fig. 2). Other application rates, such as 1–50 t/ha and 151–250 t/ha, also minimally increased the soil pH by 3% and 5%, respectively (Fig. 2). Topdressing, spreading and mixing BC on paddy soil significantly increased soil pH by 5%, 4% and 3% correspondingly. In contrast, other methods such as basal, broadcast, addition, and incorporation increased soil pH by 3%, 2%, and 1%, respectively (Fig. 2).

Furthermore, biochar is considered a controlling factor in soil carbon long-term persistence and SOC sequestration potential, leading to an increase in soil organic carbon due to the molecular structure and stability of carbon compounds by various soil amendments (Sani et al., 2023; Gross et al., 2021). Our meta-analysis study revealed that biomass feedstock such as bamboo chips, wheat straw, rice straw, and sewage sludge increased the SOC by 9%, 7%, 6%, and 3%, respectively. Overall, a general increase of ≥5% was observed in the case of SOC against all subgroups, as shown in Fig. 3. The results of our meta-analysis also predicted a significant reduction in soil bulk density, in the case of biomass feedstock such as wheat straw, sewage sludge, and rice husk. In contrast, a significant reduction in soil bulk density (8%) was observed with rice straw biochar application (Fig. S1). In the case of pyrolysis temperature, the highest decrease of bulk density (5%) of paddy soil was observed when feedstock was pyrolyzed at high temperature (>600 °C). In comparison, the lowest reduction (2%) was observed when feedstock was pyrolyzed at 350–600 °C (Fig. S1). The application rate of BC also reduced soil bulk density by 3%. Among the sub-group of the BC application methods, the basal application of BC significantly decreased the soil bulk density by 12%, in contrast to other methods such as spreading, broadcast, incorporation, mixing, and addition which also significantly reduced soil bulk density between 2% and 4% respectively (Fig. S1). BC (carbon content less than 50%) application on fine textured slightly alkaline paddy soil increased soil bulk density by 4% (Fig. S1). As a result of our findings, BC with a carbon content of less than 50% should not be applied in rice fields with fine-textured slightly alkaline soils, which can help to increase the soil bulk density and, results in a significant negative role in paddy fields.

In the case of soil porosity, the different biomass feedstocks, BC application methods, and biochar carbon content showed significant effects on the soil porosity (Fig. S2). Among the different types of feedstocks used, the wheat straw-based BC reduced paddy soil porosity by about 6%, whereas rice straw did not affect the soil porosity (Fig. S2). The incorporation method of BC is directly related to the high reduction of soil porosity (4%), while the mixing and addition methods improved the porosity of paddy soils with an increase of 2.5% and 3%, respectively (Fig. S2). Besides the BC application methods, the carbon contents of BC improved the soil's physical features, such as porosity. Concerning soil properties, the soil porosity responded with a non-significant behavior through the application of BC in coarse soils (Fig. S2). A subcategory in

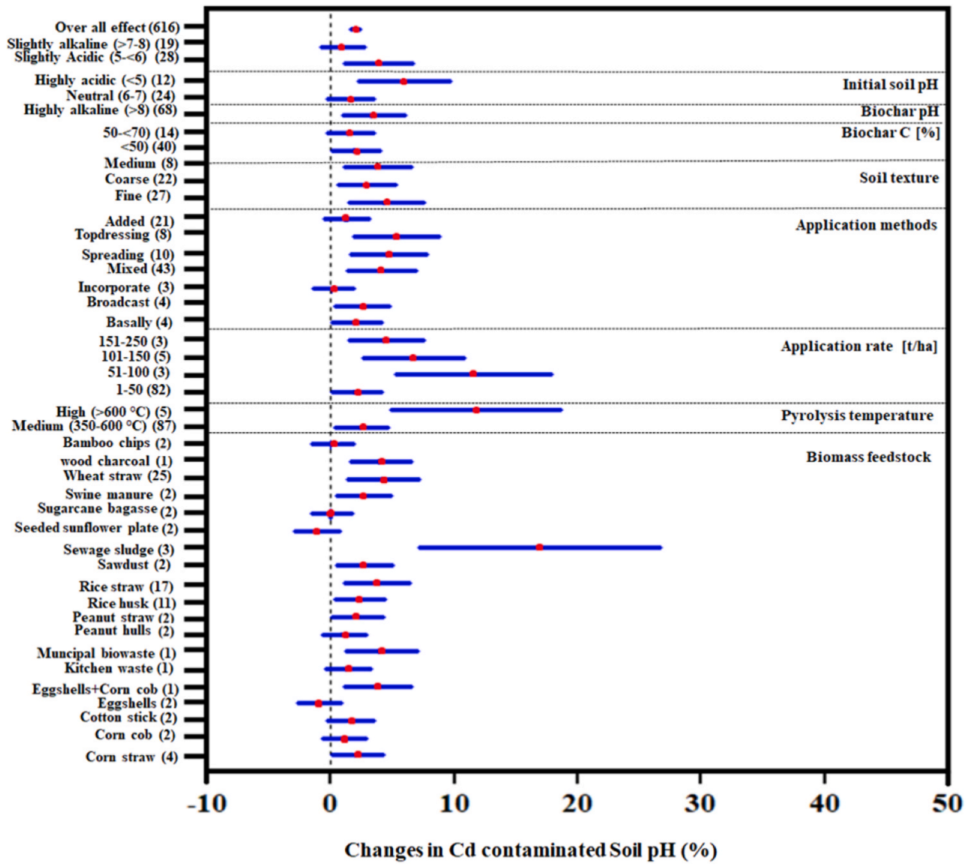

Fig. 2. Responses of biochar application among various subgroups of biomass feedstock, pyrolysis temperature, application method, soil texture, Biochar C, and initial soil pH on changes (%) in soil pH. The number in brackets indicates the number of paired observations. Error bars indicate 95% confidence intervals. Variables were significant at $p < 0.05$, if error bars did not overlap with zero.

which BC contained carbon contents of less than 50% maximally increased the soil porosity by 1% with the application of BC in paddy fields (Fig. S2).

3.3. BC amendment effects on CO_2 emission from paddy soil

Agriculture produces a substantial amount of GHG emissions, which contribute significantly to climate change, and rice fields are a large sink for GHGs such as CO_2 and CH_4 (Gupta et al., 2021; Zhang et al., 2020). BC can be considered as an organic tool to reduce CO_2 and CH_4 emissions from paddy soil. Our meta-analysis also revealed that the sewage sludge BC and bamboo chips greatly decreased the CO_2 emission by 8% and 7%, whereas the municipal biowaste BC caused the lowest decrease in CO_2 emission by 1%. In contrast, BC based on rice and wheat straw feedstock significantly increased CO_2 emission from paddy soil by 4–7%, respectively (Fig. 4). Regarding the application rate of BC, 1% reduction in CO_2 emission from paddy soil was observed when feedstock was applied at a rate of 151–250 t/ha, whereas BC was applied as 1–50 t/ha on paddy soil and caused the highest increase (3%) of CO_2 emission (Fig. 4). The biochar application method such as placement and basal spreading technique of BC application in paddy soil significantly reduced CO_2 emissions by 9% and 1%, respectively. In addition, mixing and incorporation of BC in paddy soil significantly increased CO_2 emission by 3%, and 0.5%, respectively (Fig. 4). The application of BC in paddy soil is associated with soil texture in such a way that fine-textured paddy soil significantly increased CO_2 emission by 4% (Fig. 4). Besides the soil texture categories, the BC carbon contents also limit GHG emissions, such as CO_2 emissions. A subcategory in which BC contained less than 50% carbon maximally increased the CO_2 emissions by 5% after application in paddy soils. In contrast, BC contained carbon levels ranging from more than 50% to less than 70%, increasing CO_2 emissions by 1% in paddy fields (Fig. 4). CO_2 emission is also associated with BC pH in this way that slightly alkaline BC when applied on paddy soil, reduced CO_2 emission by 0.6% while highly alkaline BC increased CO_2 emission by 2% (Fig. 4).

3.4. BC amendment effects on CH_4 emission from paddy soil

The elevated atmospheric CO_2 and temperature would further increase CH_4 emissions from paddy fields (Han et al., 2016; Jeffery et al., 2016). Therefore, BC amendment in paddy soils significantly reduces CH_4 emissions. According to our meta-analysis, municipal biowaste, sewage sludge, and sawdust pyrolyzed at temperatures above 600 °C and applied to paddy soil reduced CH_4 emissions by 2%, 1%, and 0.5%, respectively. Conversely, the high-temperature pyrolysis of wheat and rice straw increased CH_4 emissions from the soil by 4–6% (Fig. 5). The BC pyrolysis temperature was also an essential factor influencing GHG emissions. Therefore, our study revealed that the application of pyrolyzed BC at a high temperature (600 °C) amended in soil significantly reduced CH_4 emission from paddy fields by 2%, while the highest increases (4%) of CH_4 emission from paddy fields were observed after application of BC pyrolyzed at a medium range of temperatures (350–600 °C) (Fig. 5). As a result of our findings, the pyrolysis temperature for BC has an inverse relationship with the CH_4 emission. Regarding all the application methods of BC, only the basal application method caused a significant reduction in CH_4 emission by 7%, whereas BC applied to paddy soil with placement, addition, topdressing, incorporation, mixing, and spreading methodologies significantly enhanced CH_4 emission from the soil by 19%, 4%, 3%, 2%, and 1%, respectively (Fig. 5). GHG emissions from soil are also related to soil texture, with

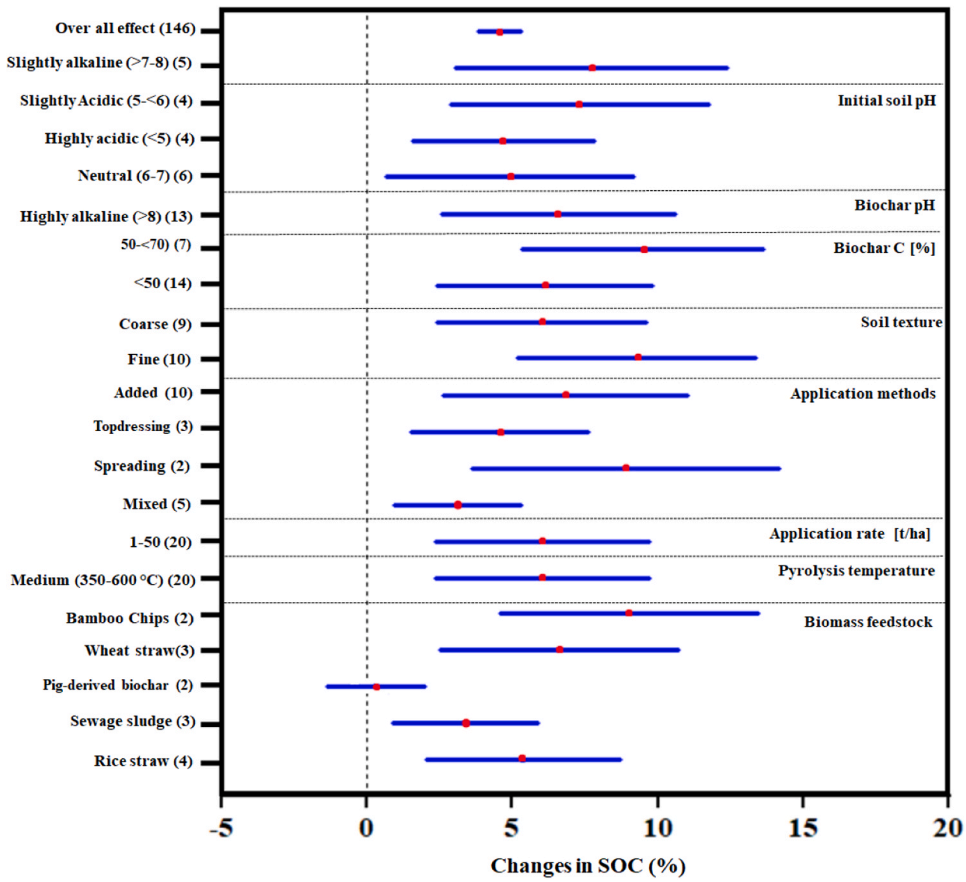

Fig. 3. Responses of biochar application among various subgroups of biomass feedstock, pyrolysis temperature, application method, soil texture, Biochar C, and initial soil pH on changes (%) in SOC. The number in brackets indicates the number of paired observations. Error bars indicate 95% confidence intervals. Variables were significant at $p < 0.05$, if error bars did not overlap with zero.

medium textured paddy soil significantly reducing CH_4 emissions by 8% after BC application (Fig. 5). Moreover, course and fine-textured paddy soil significantly enhanced CH_4 emission by 1% and 5%, respectively (Fig. 5). Therefore, our results indicated that rice plantations should be done in the medium (silt loam, loam, silt) and coarse (sandy loam, sand) textured soils that will help eliminate CH_4 emissions after BC is applied. In addition to the categories of soil texture, the BC carbon content also limited the GHG emissions, like CH_4 emissions. A subcategory in which BC contained carbon less than 50% when applied on paddy soil enhanced the CH_4 emissions by 4% in paddy fields. On the other hand, BC carbon levels ranging from more than 50% to less than 70% caused CH_4 emissions to increase marginally by 2% (Fig. 5). According to our findings, BC with less than 50% carbon levels as well as more than 70% should not be used in rice fields because it can increase the amount of CH_4 from the paddy fields. As CH_4 emissions are also linked to soil pH, CH_4 emission was very high when BC was applied to highly acid soils as compared to slightly alkaline paddy soils. While highly acidic, neutral, and slightly acidic paddy soils significantly increased CH_4 emission by 20%, 9%, and 6%, respectively (Fig. 5).

3.5. BC application effects on Cd bioavailability, uptake, translocation, and accumulation in paddy rice

3.5.1. a. BC addition reduces Cd bioavailability

Biochar is an important material for the remediation of Cd in contaminated paddy soil although, different feedstock-based BCs have variable effects on the bioavailability of Cd (Xu et al., 2022). Among different feedstocks used for evaluating Cd bioavailability in paddy soil, the top two feedstocks, the sunflower seedshlls-derived materials and rice husk, pyrolyzed at medium (350–600 °C) and high range of temperature (> 600 °C), significantly reduced the bioavailability of Cd in paddy soil by 24% and 12% respectively. Whereas peanut straw-based BC enhanced bioavailable Cd in paddy soil by 5% (Fig. 6). In comparison, BC based on corn straw, hickory nutshells, kitchen waste, and maize straw feedstocks increased immobility and decreased bioavailability of Cd in soil by 3%, 7%, 4%, and 1%, respectively (Fig. 6). The remaining feedstock (peanut shells) maximally increased the Cd bioavailability in paddy soil as shown in Fig. 6. Regarding pyrolysis temperature, the mobilization of Cd in soil was reduced by 4% when feedstock was pyrolyzed at high and low temperatures (Fig. 6). The varying rate of BC application also influenced the available Cd in soil, such as an increase in the BC application rate, reduced the Cd content in the soil. BC applied at the rate of 101–151 t/ha highly limits the bioavailable Cd in soil by 14% whereas, 1–50 t/ha BC caused the lowest reduction of Cd by 4% (Fig. 6). All types of soil textures reduced the mobilization of Cd by 64% and restricted its translocation to rice plant through roots (Fig. 6).

3.5.2. b. BC addition limits Cd transfer from paddy soil to rice roots

Due to its high toxicity, Cd contamination in paddy fields is considered a severe health hazard, and the BC amendment restricts Cd's uptake, translocation, and accumulation in rice plants (Li et al., 2021; Liu et al., 2020). BC based on kitchen waste, peanut hulls, and corn cob feedstock reduced the roots' Cd uptake by 22%, 21%, and 15%, respectively. Meanwhile, BC based on swine manure and rice straw feedstock minimally reduced the translocation of Cd in roots by 2% (Fig. S3). In comparison, single-pyrolyzed BC based on oil palm fiber did not affect the Cd remediation and significantly increased (7%) the mobility of Cd from soil to roots with a positive effect size. Besides,

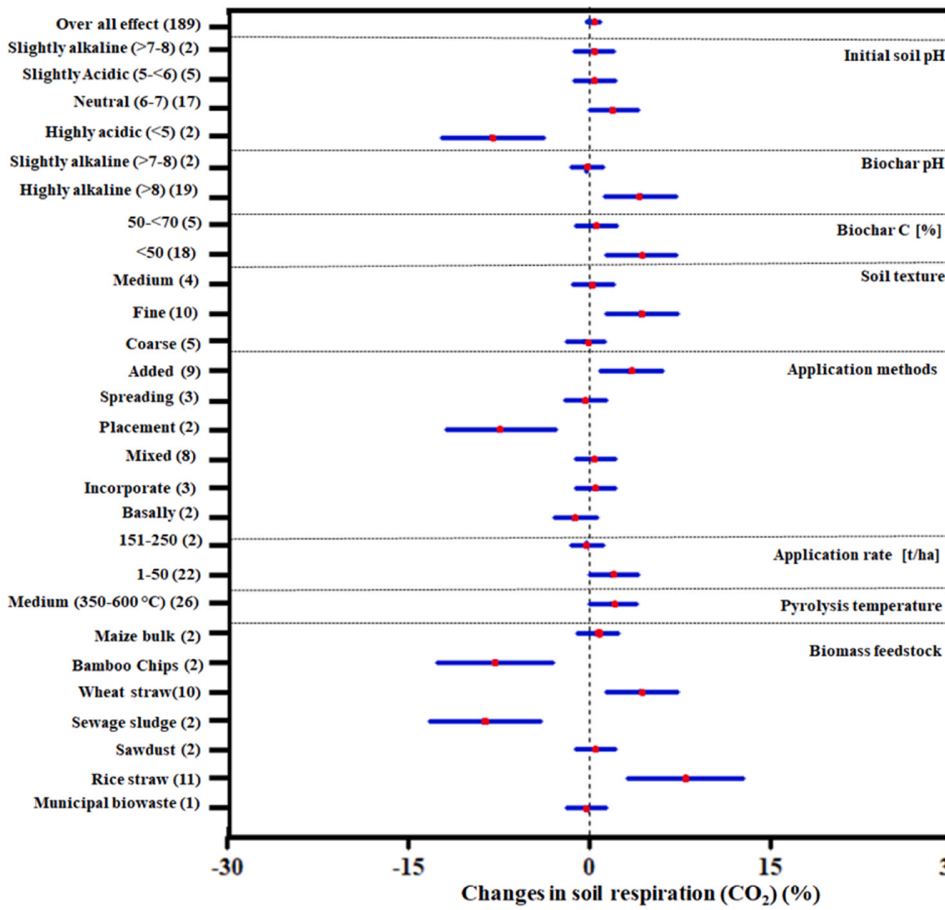

Fig. 4. Responses of biochar application among various subgroups of biomass feedstock, pyrolysis temperature, application method, soil texture, Biochar C, and initial soil pH on changes (%) in soil respiration (CO_2). The number in brackets indicates the number of paired observations. Error bars indicate 95% confidence intervals. Variables were significant at $p < 0.05$, if error bars did not overlap with zero.

single pyrolyzed BC and co-production of BC from eggshells and corncob could not limit the Cd mobility; therefore, Cd translocation is enhanced by 20% (Fig. S3). The pyrolysis of BC at a medium range of temperatures (350–600 °C) and spreading on the soil at 151–250 t/ha effectively reduced Cd translocation from soil to rice roots by 8% (Fig. S3). All application methods such as spreading, addition, mixing, topdressing, and basal method showed Cd reduction in rice roots by 12%, 6%, 8%, 5%, and 2%, respectively (Fig. S3). About 9% reduction of Cd in roots was observed when BC carbon was more than 50% to less than 70%. Furthermore, the results of our meta-analysis revealed a 19% Cd reduction of Cd in rice plant roots, grown in slightly alkaline soils (Fig. S3).

3.5.3. c. BC effects on Cd translocation in rice shoots

Cadmium enters rice roots from soil solutions and is translocated to shoots via xylem pathways, and BC-amended soils limit the Cd translocation (NaziaTahir et al., 2021). The four most effective BCs based on cotton sticks, kitchen waste, peanut hulls, and rice husk pyrolyzed at a temperature range of 350–600 °C restricted the Cd translocation from rice roots to shoots by 22%, 27%, and 20%, and 19%, respectively. After application in paddy fields, eggshells corn cob, eucalyptus wood waste, and sugarcane bagasse-based BC did not affect the Cd reduction or enhancement in shoots (Fig. S4). Other BC based on different feedstocks (corn straw, swine manure, corncob, eggshells, sewage sludge, sunflower seedshells-derived materials, municipal biowaste, oil palm fiber, peanut straw, rice straw, sawdust, and wheat straw except for wood charcoal) also significantly reduced the Cd transfer from roots to shoots (Fig. S4). The varying rate of BC application also influenced Cd translocation to shoots, such as the rate (1–50 t/ha) caused the reduction of Cd in shoots, as indicated in Fig. S4. However, this direct relationship between increased BC rate and reduced Cd content in the plant shoots when BC applied at the rate of 1–50–51–100 t/ha and reduced Cd translocation by 14–8%. Meanwhile, the highest BC rate (101–250 t/ha) decreased the Cd mobility from root to shoot by 6%, which was lower than that of the lowest BC rate (Fig. S4). Among the categories of BC application methodology, the spreading, and mixing of BC usage in paddy soil greatly decreased the Cd translocation rate by more than ten percent. In contrast, other individual methods were only responsible for a less than 10% reduction in Cd translocation from rice roots to shoots (Fig. S4).

3.5.4. d. BC effects on Cd accumulation in rice grains

The primary step for determining the Cd accumulation in the grains is the remobilization of Cd from rice shoots to the grains (Zhang et al., 2018), and the Cd remobilization efficiency following the addition of BC. In our study, sawdust, rice husk, and bamboo chips-based BC reduced the Cd accumulation in rice grains below twenty percent, except sugarcane bagasse BC which reduced Cd by 25% (Fig. 7). After sawdust BC, the rice husk BC was the second most effective pyrolyzed feedstock, effectively reducing Cd content in rice grains by 13%. In the case of pyrolysis, our results revealed that the BC feedstock pyrolyzed at the medium range of temperatures (350–600 °C) and mixed in the paddy soil at a rate of 151–250 t/ha significantly reduced Cd accumulation in rice grains (Fig. 7).

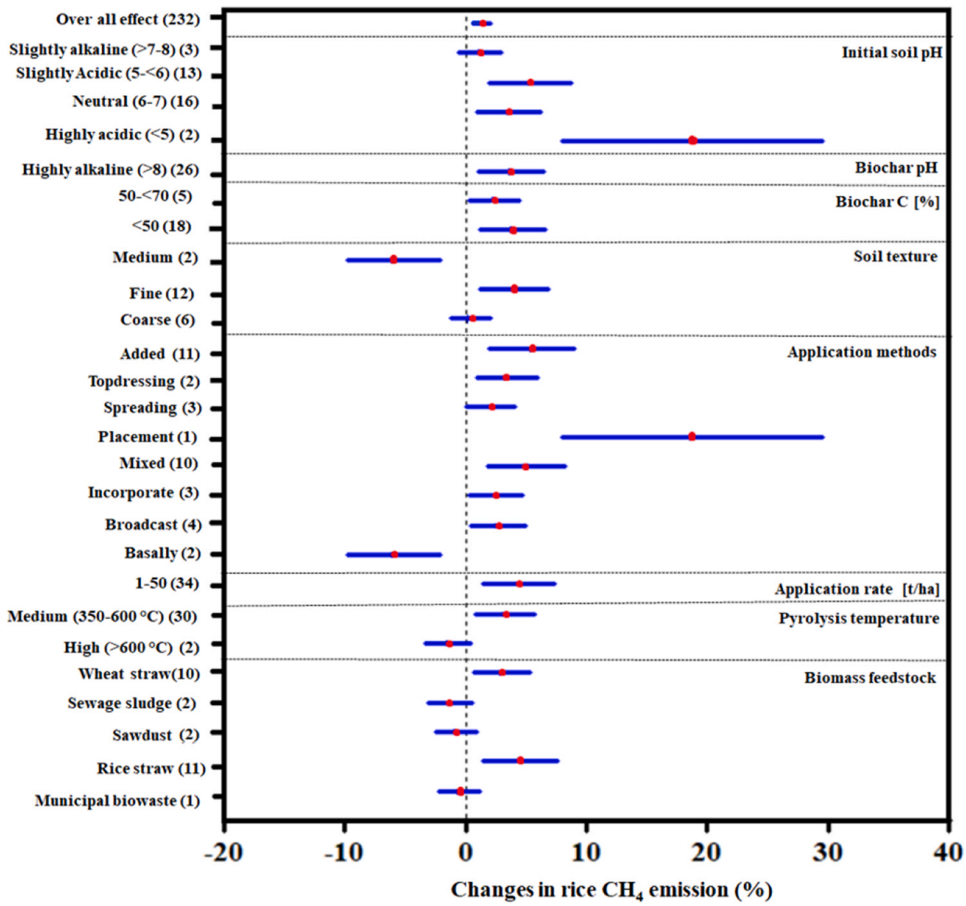

Fig. 5. Responses of biochar application among various subgroups of biomass feedstock, pyrolysis temperature, application method, soil texture, Biochar C, and initial soil pH on changes (%) in rice methane (CH_4) emission. The number in brackets indicates the number of paired observations. Error bars indicate 95% confidence intervals. Variables were significant at $p < 0.05$, if error bars did not overlap with zero.

3.6. Rice yield response to BC application

Biochar amendments in paddy soil not only improved the soil physio-chemical properties and reduced Cd concentration in rice plants but also significantly enhanced the rice yield (Irshad et al., 2022). Among different feedstocks used for evaluating rice yield, cotton stick-based BC pyrolyzed at medium (350–600 °C) and high range of temperature (> 600 °C), significantly enhanced yield by 37%. Whereas municipal bio-waste BC was responsible for the lowest increase (3%) in rice yield. In comparison, only two feedstock, corncob, and hickory nut shells, reduced rice yield by 8% and 5%, respectively (Fig. 8). About pyrolysis temperature, the rice yield was enhanced by 6% when feedstock was pyrolyzed at high and low temperatures (Fig. 8). In our results, BC application rate showed the highest increase (25%) of rice yield when applied as 51–100 t/ha whereas, the increased rate of BC (101–150 t/ha) caused lowest increase (10%) of rice yield (Fig. 8). Moreover, addition and basal application of BC in paddy soil is a significant method of BC application for enhancement of paddy yield by 18% and 16%, respectively. Moreover, it was also observed that fine and medium-textured soil enhanced the yield by more than 10% as compared to coarse-textured soil (Fig. 8).

4. Discussion

4.1. BC-induced changes in soil properties

The physical and chemical characteristics of soils affect the amount of air, inorganic nutrients (nitrogen, phosphorus), biostimulants, and water that are necessary for plant growth and development, and BC treatment enhances soil fertility and health (Abbott et al., 2018; Shi et al., 2019; Wong et al., 2020; Cardone et al., 2020; Irshad et al., 2020; Schmidt et al., 2021; Wang et al., 2022). BC is a carbon-enriched material produced by the pyrolysis of organic biomass such as crop residues, manure, and wood (Albert et al., 2021; Ghodake et al., 2021). BC application significantly reduced soil bulk density and soil porosity of paddy fields (Fig. S1, S2), and there is a close relationship between bulk density and porosity (Kakaire et al., 2015). However, the percent change of different BC may vary depending on pyrolysis temperature, BC application methods, BC carbon contents, soil texture, and the initial soil pH; whereas the percent change of various BC on soil porosity responded differently based on BC application methods and the BC intrinsic carbon contents (Jia et al., 2023). Interestingly, our study results demonstrated that the percent change of Cd-contaminated soil pH may also vary depending on the BC application rate and methodology (Fig. 2).

4.1.1. BC-induced changes in soil pH

Biochar application enhanced the soil pH due to base cations and ash amounts. As biomass feedstock has basic cations, and after fast pyrolysis, it is converted into carbonates, hydroxides, and oxides and contributes to increasing soil pH (Bashir, et al., 2018). Our results showed that different BC feedstock applied in paddy soil resulted in various responses but the sewage sludge showed an 18% increase in soil pH and these findings were supported by (Bashir et al., 2018). However, feedstock type and pyrolysis conditions play important roles in determining the effect of BC on soil pH. BC produced by fast pyrolysis (high temperature) generally has more alkaline pH and higher carbonate contents compared

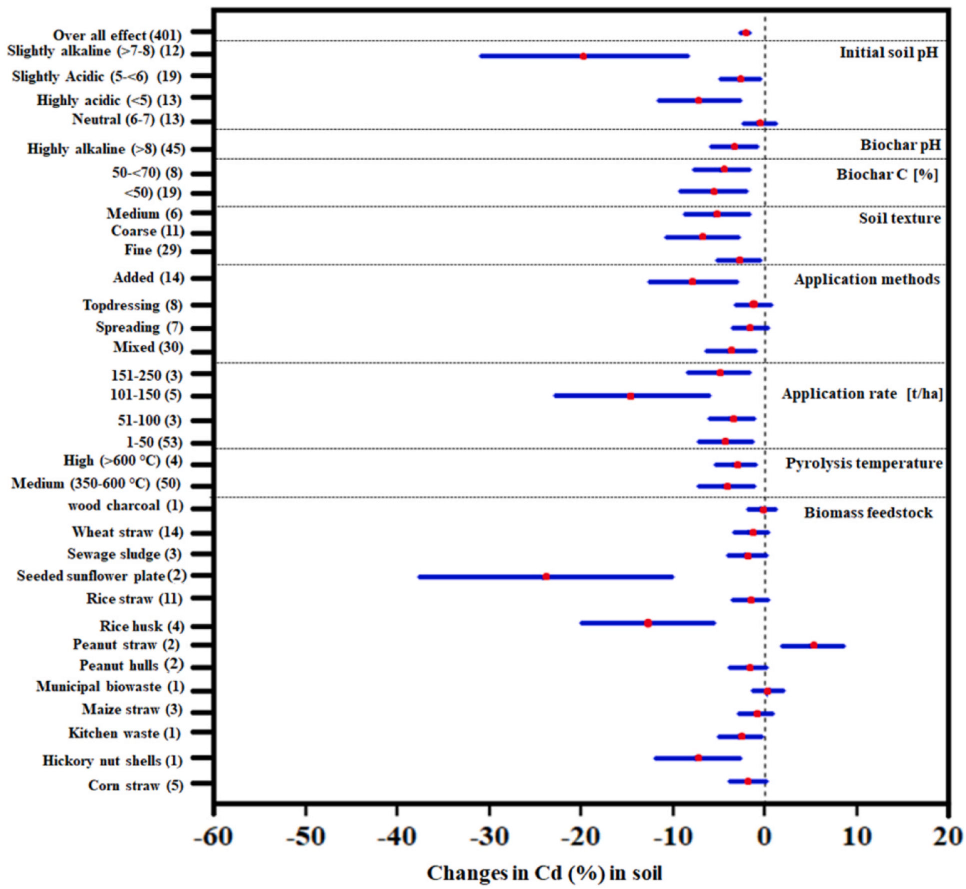

Fig. 6. Responses of biochar application among various subgroups of biomass feedstock, pyrolysis temperature, application method, soil texture, Biochar C, and initial soil pH on changes Cd (%) in soil. The number in brackets indicates the number of paired observations. Error bars indicate 95% confidence intervals. Variables were significant at $p < 0.05$, if error bars did not overlap with zero.

to BC prepared at a lower temperature (Wang et al., 2013). Regarding pyrolysis temperature, our analysis results showed a 10% increase in paddy soil pH when feedstock was pyrolyzed at high temperatures (>600 °C). In contrast, a 3% increase was observed in the case of feedstock pyrolyzed in the temperature range of 350–600 °C as stated by (Wang et al., 2013). Interestingly, others findings were also supported by Tomczyk et al. (2020); who indicated that the BC produced at high pyrolysis temperature significantly increased soil pH. Our meta-analysis revealed that BC application rate also influenced soil pH. The BC applied at the rates of 51–100 and 101–151 t/ha significantly enhanced soil pH by 10% and 5%, respectively but 1–50 and 151–250 t/ha applied BC showed a 3% and 5% increase in soil pH, respectively. Moreover, topdressing, spreading, and mixing of BC on paddy soil increased the soil pH by 5%, 4%, and 3% while basal application, broadcast, addition, and incorporation of BC increased soil pH by 3%, 2%, and 1%, respectively (Fig. 2). We have found that sunflower seed shells-derived materials BC pyrolyzed at high temperature (>600 °C) and top-dressed on paddy soil as 51–100 t/ha significantly increased the pH of Cd-contaminated soil. Top-dressing is a technique that helps to improve the soil by applying BC and Rex et al. (2015) claimed that continuous top-dressing of temperate grassland sites by fast pyrolyzed (600 °C) of *Miscanthus* straw-based BC not only significantly improved soil physically but also shifted microbial community of the experimental site after 2.6 years. The oxygen-containing functional groups -COOH and -OH found on the surface of sunflower-derived BC (rapid pyrolysis) together with their organic anions (-COO- and -O-) form a pH buffering mechanism by absorbing protons through deprotonation processes at high pH and protonation reactions at low pH, these functional groups boost the capacity of the pH buffer (pHBC) (Alam et al., 2018; Lu et al., 2022) therefore, BC could enhance Cd-contaminated soils pH.

4.1.2. BC-induced changes in soil organic carbon

Biochar affects the soil's organic carbon positively, as carbon is an important nutrient that maintains rice growth, development, and productivity. A massive quantity of carbon is present in BC due to its preparation at high pyrolysis temperatures. BC appeared to alter the levels of SOC, but the mechanisms remained unclear (Jing et al., 2020; Liu et al., 2022). Our study revealed that bamboo chips, wheat straw, rice straw, and sewage sludge BC increased the SOC by 9%, 7%, 6%, and 3%, respectively. These results were supported by Jing et al. (2020), observation which showed that the application of straw-based BC enhanced the SOC contents, due to the high organic carbon content present in the BC. Jing et al. (2020) also found that BC greatly influenced the CO_2 emissions and increased soil carbon sequestration. Our results showed that bamboo chips, wheat and rice straw, and sewage sludge BC when either added, top-dressed, spread, or mixed in fine or coarse paddy soils with an application rate of 1–50 t/ha, increased the SOC. Our findings were supported by Ku et al. (2019); who claimed that rice straw compost and rice straw-based BC significantly enhanced the SOC by 11%. Additionally, the incorporation of rice straw in early and late growth stages into paddy fields significantly enhanced the total SOC by 7–28% when compared to the control (Wang et al., 2015). The application of straw-based BC could also increase soil water conservation, resulting in the development of an anaerobic environment in the paddy soils, thus enhancing soil carbon sequestration by decreasing carbon release through soil respiration (Chu et al., 2023; Wang et al., 2015). Previously, Wang et al. (2015) studied that water contents in the soil significantly and positively correlated with the total SOC contents,

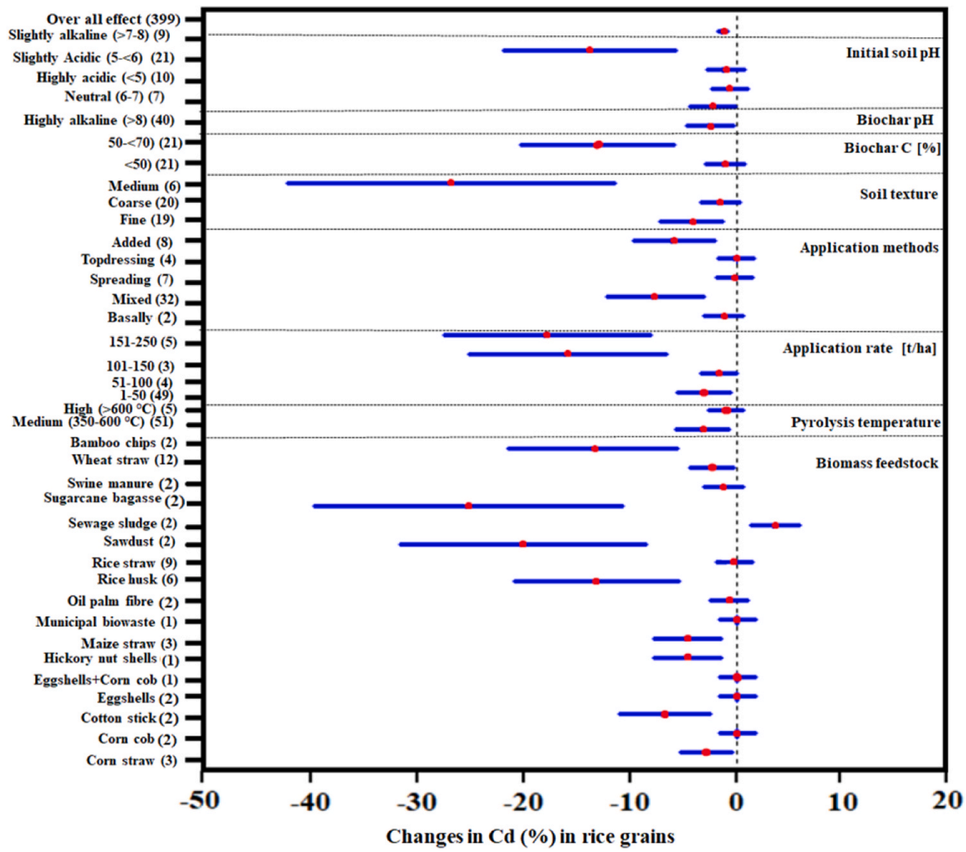

Fig. 7. Responses of biochar application among various subgroups of biomass feedstock, pyrolysis temperature, application method, soil texture, Biochar C, and initial soil pH on changes Cd (%) in rice grains. The number in brackets indicates the number of paired observations. Error bars indicate 95% confidence intervals. Variables were significant at $p < 0.05$, if error bars did not overlap with zero.

which resulted in better availability of oxygen as well as total soil nitrogen contents in the paddy soils of China.

4.1.3. BC-induced changes in soil bulk density

Biochar (including their nanobiochar counterparts) can differ in their physical properties such as feedstock type, pyrolytic conditions, BC carbon contents, BC application rate, and methodology (Sani et al., 2023). Moreover, the interaction between biomass feedstock type and pyrolysis conditions for BC preparation can later affect paddy soils' physical and chemical properties (Singh et al., 2022). Our results indicated that rice straw, wheat straw, rice husk, and sewage sludge pyrolyzed at a high temperature (>600 °C) having 50%-70% carbon contents basally applied in fine-textured paddy soil having a slightly alkaline pH significantly reduced soil bulk density (Fig. S1). Our results were in line with (Rorat et al., 2019) who stated that the sewage sludge composition includes 50%-70% organic matter which can influence the soil compaction and reduced soil bulk density (Abu-Hamdeh and Reeder, 2000). Regarding pyrolysis conditions, Ippolito et al. (2020) found that different feedstocks and pyrolysis conditions produced different amounts of BC and changed the BC's physicochemical properties. Slow pyrolysis (low temperature) produced equal quantities of gas, liquid, and solid products whereas, the high temperature in fast pyrolysis delivered higher bio-oil yields and lower biochar quantities and gas production (Qambrani et al., 2017; Sohi et al., 2009). Interestingly, the slow pyrolysis process appeared to exert greater influence on biochar's physicochemical properties as compared to fast pyrolysis conditions. Slow pyrolysis produced BC with a higher ash content than BC produced at high temperatures (Ippolito et al., 2020). According to our results, sewage sludge required high pyrolysis temperature during preparation to attain a significant reduction of bulk density because it has high water content. Blanco-Canqui (2017) claimed that the differences in particle densities and sizes of BC showed variations in reducing soil bulk density on fine-textured and course-textured soil. Another factor determining the decrease in bulk density of paddy soil with BC application is the BC carbon contents. Interestingly, the carbon contents of BC have an inverse relationship with the bulk density; as the carbon content increases, the density decreases due to the difference in particle size (Blanco-Canqui, 2017). Our meta-analysis also showed that the percent change (%) of bulk density was diminished after using BC with high (50–70%) carbon as stated by Blanco-Canqui (2017).

4.1.4. BC-induced changes in soil porosity

Soil porosity significantly contributes to plant health due to its major role in soil water-holding capability and oxygen. BC application affected the soil's physical properties, such as soil porosity. Our results predicted that wheat straw-based BC reduced the soil porosity by 6%, while rice straw-based BC had no significant effect on soil porosity of Cd-contaminated paddy soils (Fig. 3). Conversely, Blanco-Canqui (2017) claimed that BC application could increase soil porosity by 2–4% because it contained longitudinal micro to macropores that resultantly altered the soil porosity (Tomczyk et al., 2020). Previously, it was explained that the rice straw-based BC improved the microporosity and ultra-microporosity of soil by both direct pore contribution and the creation of new pores in BC-amended soil as observed under scanning electron microscopy (Wen et al., 2021). Similar to our meta-analysis, one of the studies found no significant difference between the effect sizes of manure and plant-based BC in terms of soil porosity (Singh et al., 2022). In the case of BC application method, the BC incorporation reduced the soil porosity (4%), while the mixing and addition methods improved the porosity of paddy soils by 2.5% and 3%, respectively. The

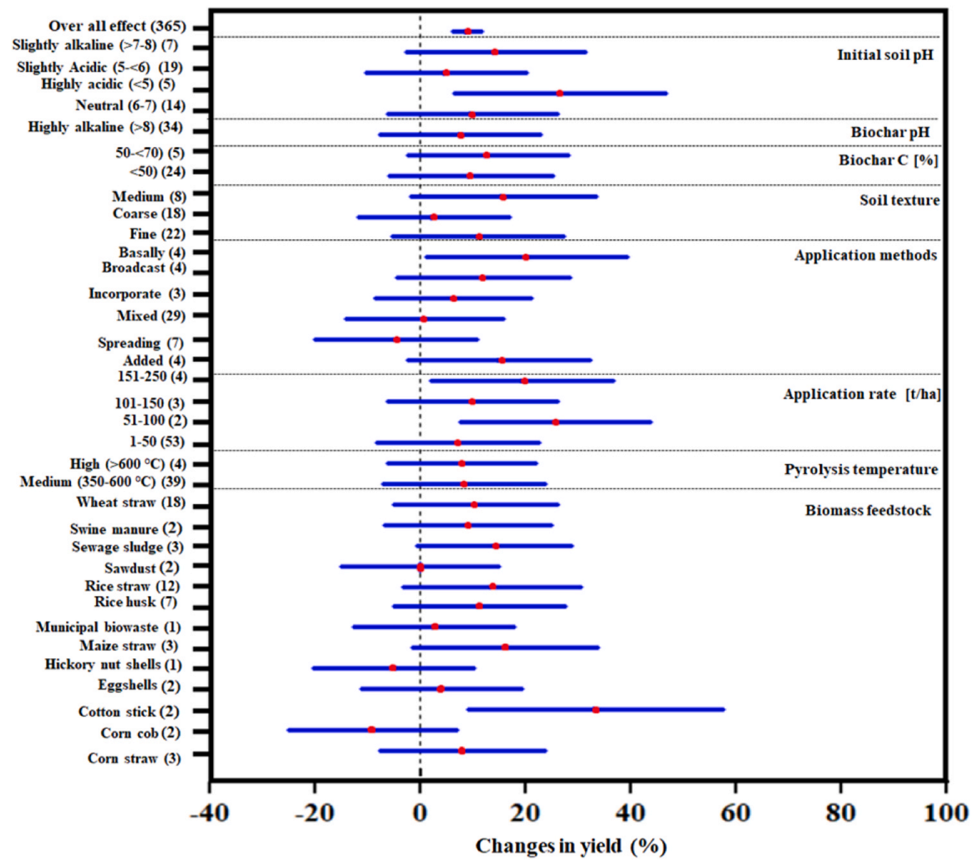

Fig. 8. Responses of biochar application among various subgroups of biomass feedstock, pyrolysis temperature, application method, soil texture, Biochar C, and initial soil pH on changes Cd (%) in rice yield. The number in brackets indicates the number of paired observations. Error bars indicate 95% confidence intervals. Variables were significant at $p < 0.05$, if error bars did not overlap with zero.

study results were also in line with our investigation, reporting that the soil porosity was significantly reduced by 5% (w/w) with the biochar application in paddy soils (Zheng et al., 2019).

4.2. BC effects on CO_2 and CH_4 emission from paddy soil

A substantial amount of GHGs emitted from anthropogenic activities significantly contribute to climate change and global warming (Cao et al., 2019; Han et al., 2016; Raihan and Tuspekova, 2022). Our findings showed that rice and wheat straw-based BC increased CO_2 emission by 4–7% while bamboo chips and sewage sludge BC reduced CO_2 by 7–8% (Fig. 4), and these variations depend on BC application rate, and methodology, soil texture, BC carbon content, and BC pH (Fig. 4 & 5). Our findings showed that placing sewage sludge BC in highly acidic soils with less than 50% carbon contents applied as 151–250 t/ha on medium as well as coarse-textured paddy soil reduced CO_2 emission (Fig. 4). Our results were in alignment with the results of Khan et al. (2013) who stated that in the United States, about 6.2 million metric tons dry weight of sewage sludge produced per year and applied as BC after pyrolysis and significantly reduced GHGs. Additionally, Joshi et al. (2022) also demonstrated that BC formed by fast pyrolysis of sewage sludge is a promising tool and soil additive for significantly reducing CO_2 and CH_4 emissions. Li et al. (2022) also elaborated that biochar derived from mixed sewage sludge and pine sawdust significantly reduced CO_2 emissions from soil. Additionally, the effect of BC type on CO_2 emission, and the interaction of soil texture and BC showed various effects on GHG emissions. The results of our study indicated that slightly alkaline BC reduced CO_2 emission while highly alkaline BC increased CO_2 emission. Similarly, both medium and coarse-textured paddy soil significantly reduced CO_2 emission after BC application (Fang et al., 2014; He et al., 2016); while Sun et al. (2014) claimed that reduced CO_2 emission was observed in fine-textured soil as compared to coarse-textured BC-amended soils.

Methanogenesis is a microbial catalytic process in which anaerobic degradation of organic matter to gaseous products such as CO_2 and CH_4 widely refers to soil ecosystems such as rice cropping systems (Conrad, 2020). BC addition in paddy soil reduced the emission of GHGs by changing the microbial community and regulating the methanotroph diversity. Methanotrophs are bacteria or archaea that grow aerobically and anaerobically to consume methane and reduce CH_4 emissions (Qi et al., 2021). In our meta-analysis, municipal waste, sawdust, and sewage sludge BC significantly decreased the CH_4 emissions by 2%, 1%, and 0.5%, respectively (Fig. 5). The variation of CH_4 emissions was based on percent change concerning BC types with pyrolysis temperature, BC application methods, BC carbon contents, soil texture, and initial soil pH (Fig. 5). Our results indicated that wheat and rice straw-based BC pyrolyzed at high temperature increased CH_4 emission by 4–6% while municipal biowaste pyrolyzed at high temperature and having carbon contents more than 50% basally applied on medium textured (silt loam, loam, and silt) paddy soil having a slightly alkaline pH significantly reduced CH_4 emission. Our findings were supported by Shao et al. (2019); who revealed that pyrolyzed municipal biowaste reduced the CH_4 emission from the paddy soil. Contrary to our results, Xiao et al. (2018) claimed that the lowest CH_4 emission was observed from paddy soil when rice straw-based BC was applied. Therefore, more ash content in BC can increase GHG sorption in mineral oxides and decreased the GHG emissions (Butnan et al., 2016).

4.3. BC impacts on Cd immobilization in paddy soil and accumulation in rice

Currently, agricultural soils are more prone to heavy metal and metalloid contamination due to their mobility and accumulation in crops (Liu et al., 2012; Yang et al., 2018). Anthropogenic activities such as agricultural inputs, mining, smelting, and coal combustion are mainly responsible for releasing Cd into the soil (Wang et al., 2021). Results of our meta-analysis revealed that sunflower seed-shells-derived materials, and rice husk pyrolyzed at a medium range of temperatures (350–600 °C) and either added, top-dressed, spread, or mixed in Cd-contaminated soil applied as 101–151 t/ha, significantly reduced the bioavailability and enhanced the immobilization of Cd in paddy soil (Fig. 6). Sunflower seedshells-derived materials BC feedstocks has oxygen-containing functional groups (-COOH, -OH, etc.) on their surface and could generate a complex formation with Cd in amended soil, that reduced Cd bioavailability and increased their immobilization within the rhizosphere (Ibrahim et al., 2016; Silva et al., 2020). Previous outcomes were in line with our results, which revealed that co-pyrolysis of peanut and maize-based BC significantly enhanced oxygen-based functional groups on the BC surface for more complex formation with Cd (Atilano-Camino et al., 2022; Xu et al., 2022). Besides BC usage, adding soil amendments like compost, vermicompost and insect frass, are also practical organic and inorganic process to improve soil properties, fertility and plant health (Abbott et al., 2018; Wong et al., 2020; Sani and Yong, 2022; Lopes et al., 2022). Interestingly, BC could be considered the most efficient tool for stabilizing Cd in soil than any other amendments as revealed by Irfan et al. (2021). Various postulated mechanisms, such as precipitation, electrostatic interaction, ion exchange, and surface adsorption, were involved in the interaction of BC particles with heavy metals and enhanced Cd immobilization (Chen et al., 2018; Peng et al., 2018). BC application increased soil pH and prevailed electrostatic interaction in Cd adsorption depending on soil solution pH. Cd stabilization due to BC application depends on various BC characteristics, including surface heterogeneity, a large surface area, and a variety of functional groups that adsorb heavy metals on the soil surface (Hu et al., 2020; Liu et al., 2023). Moreover, BC microporosity and excessive soluble salts increased heavy metals' immobilization by precipitation and surface sorption (Irfan et al., 2021). Moreover, the immobilization of Cd ions in soils is caused by the development of soil-BC complexes due to BC amendment, which could increase soil surface negative charge (Nkoh et al., 2021).

Roots are the main pathway for Cd translocation to aerial parts of rice plants, and reduction in Cd accumulation into rice grains is a priority for food safety (Li et al., 2022). Our findings showed that BC application can significantly reduce the Cd uptake by rice roots and its translocation into the shoots and grains. Different BC effects on Cd uptake by roots and transfer into the shoots, and grains vary depending on pyrolysis temperature, BC application rate, and methodology (Fig. 7 and Fig. S3, S4). According to our study findings, the kitchen waste, peanut hulls, and corn cob significantly reduced the roots' Cd uptake (Fig. S3). While the kitchen waste and peanut hulls pyrolyzed at a medium range of temperatures and spread on the paddy soil applied as 51–100 t/ha reduced the roots' Cd uptake by 8%, and spreading, addition, mixing, topdressing, and basal application methods showed a reduction of Cd in rice roots (Fig. S3). These findings were supported by Bashir, et al., (2018); who stated that the limited translocation of Cd into the plants could be due to soil-applied BC which may neutralize the H^+ ions in Cd-polluted soil solution, significantly increased the negative surface sites for Cd complexation, and declinef the Cd uptake by plant tissues (Bashir, Hussain, et al., 2018; Bashir, Rizwan, et al., 2018; Bashir, Shaaban, et al., 2018).

Similarly, the cotton sticks, kitchen waste, peanut hulls, and rice husk pyrolyzed at a temperature range of 350–600 °C, restricting the Cd translocation from rice roots to shoots, while BC application rate and application methods significantly reduced the Cd translocation from rice roots to the shoots (Fig. S4). Our results were consistent with (Xu et al., 2020), revealed that kitchen waste-based BC significantly reduced Cd translocation in swamp cabbage. Moreover, Suksabye et al. (2016) found that sawdust fly ash, bagasse fly ash, and rice husk ash on paddy soil for Cd translocation to rice plants. Whereas sugarcane bagasse, sawdust, rice husk, and sewage sludge-based BC feedstock pyrolyzed at the medium range of temperatures (350–600 °C) and mixed in the paddy soil at a rate of 151–250 t/ha seemed to be very effective in reducing Cd in rice grains (Fig. 7). These findings were supported by Suksabye et al. (2016); revealed that sawdust showed the highest significant effect for reducing Cd accumulation in rice grains. Besides, the individual feedstock pyrolysis, co-pyrolysis of blended feedstocks is the most advanced strategy to remediate heavy metal phytotoxicity, therefore Meng et al. (2018) found that the co-pyrolyzed rice straw and swine manure BC significantly reduced the soil bioavailable Cd. Moreover, Wan et al. (2020) also evaluated the co-pyrolyzed chicken and swine manures on Cd-contaminated paddy soil and significantly reduced the levels of Cd in rice plants.

4.4. BC improves rice yield

Modern agriculture's greater reliance on synthetic fertilizers is essential for increasing crop production but may inevitably affect the grain quality negatively. Interestingly, BC application is a well-known safe alternative for improving soil fertility by increasing soil water holding capacity, reducing soil bulk density, increasing soil pH, and porosity, and immobilizing contaminants in soil, thereby potentially enhancing the grain yield (DeLuca et al., 2015; Lee et al., 2015; Ali et al., 2022). In China, anthropogenic activities caused a serious issue by increasing the levels of toxic heavy metals such as Cd in rice fields. Therefore, BC amendment in rice fields is an important tool for improving the rice yield grown in Cd-contaminated soils (Irshad et al., 2020). A significant improvement in rice grain yield was observed through the BC addition, leading to an improved soil environment such as increased microbial metabolism, nutrient bioavailability, earthworm population, and enzymatic activities (Cayuela et al., 2014; Zhang et al., 2021; Xu et al., 2018). According to the results of the meta-analysis, the overall increase in rice yield was more than 20%, and the largest increase in rice yield was observed in the case of cotton sticks pyrolyzed at medium and high temperatures (>600 °C) and basely applied as 51–100 t/ha in Cd contaminated paddy soil (Fig. 8). Moreover, it was found that BC application in medium and fine-textured soils enhanced the yield as compared to coarse-textured soils. Our results were supported by Rehman ur et al. (2021); indicating that cotton sticks BC significantly reduced the soil bioavailable Cd contents in rice roots, shoots, and grains; with concomitant grain yield by about 26.7%. In our meta-analysis, similar results were observed for rice husk-based BC that enhanced the rice yield by 16% as compared to the control and our finding followed another experiment which found a 55% increase in rice yield by using rice husk-based BC as compared to the control (Isimikalu et al., 2022). Moreover, (Liu et al., 2022) also revealed that BC application increased rice yield by 10.7%. Previously, it was found that the rice yield was significantly increased by 10.7% and 4.8% through bamboo and rice straw-based BC respectively (Liu et al., 2016).

5. Conclusions

This meta-analysis evaluated comprehensively the effects of BC application on greenhouse gas emissions,Cd bioavailability and accumulation, and rice yield in Cd-contaminated paddy soils. The analysis was based on data from 100 published articles, encompassing 1576 observations. The results demonstrated that the BC amendment is an effective approach for mitigating climate change impacts and improving food safety in the rice production system. BC increased the soil pH, soil organic carbon content, and porosity while concomitantly reducing the soil bulk density. These improvements in soil physicochemical properties facilitated a 7–8% reduction in carbon dioxide and a 2% reduction in methane emission from paddy soils. Specifically, BC dramatically reduced the bioavailability of toxic Cd in contaminated paddy soils, limited its uptake, translocation, and accumulation in rice plants. The most effective BC feedstocks for Cd immobilization were sunflower seedshells-derived materials, rice husk, peanut hulls, and kitchen waste. BC application rates of 101–151 t/ha were optimal for restricting Cd phyto-availability. Sawdust and rice husk BCs were particularly effective in reducing Cd in rice grains by 25% and 13% respectively. Overall, BC amendments enhanced the rice yields by over 20%, with cotton stick BC boosting yields at an impressive level of 37% in Cd-contaminated soils. The findings highlighted the tremendous potential of using BC as a multi-faceted soil management strategy for improving rice productivity, food safety, environmental resilience and sustainability under the looming threat of climate change.

CRediT authorship contribution statement

Haifa Abdulaziz Sakit Alhaithloul: Funding acquisition. **Muhammad Sagir:** Resources. **Shafeeq UR Rahman:** Validation, Formal analysis. **Jean Wan Hong Yong:** Resources, Funding acquisition. **Muhammad Rizwan:** Writing – review & editing, Validation. **Hongchao Zuo:** Supervision. **Habib Ali:** Software. **Safdar Bashir:** Writing – review & editing. **Ibtisam Mohammed Alsudays:** Funding acquisition. **Muhammad Athar Khaliq:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declared that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that has been used is confidential.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2024.116204.

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